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SPATIAL LEARNING AND REASONING SKILL.(U)
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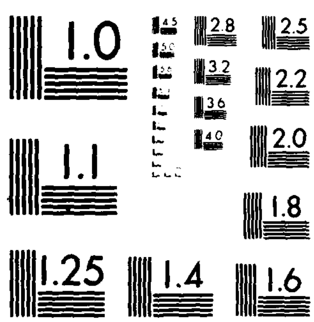

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Spatial Learning and Reasoning Skill

Sarah E. Goldin and Perry W. Thorndyke

The research described in this report was sponsored by the U.S. Army Research Institute for the Behavioral and Social Sciences under Contract No. MDA903-79-C-0549. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

Library of Congress Cataloging in Publication Data

Goldin, Sarah E., 1953-
Spatial learning and reasoning skill.

"R-2805-Army."
Prepared for the United States Army

Bibliography: p.
1. Geographical perception. 2. Military education--United States. I. Thorndyke, Perry W. II. United States. Army
III. Title.
G71.5.G64 623.7'1 81-12115
ISBN 0-8330-0346-1 AACR2

The Rand Publications Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

Published by The Rand Corporation

12 11 LEVEL II

R-2805-ARMY

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July 1981

Prepared for the
U.S. Army Research Institute
for the Behavioral and Social Sciences

Rand
SANTA MONICA, CA. 90406

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER R-2805-ARMY	2. GOVT ACCESSION NO. AD-A107 345	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Spatial Learning and Reasoning Skill.		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Sarah E. Goldin, Perry W. Thorndyke		8. CONTRACT OR GRANT NUMBER(s) MDA903-79-C-0549
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation 1700 Main Street Santa Monica, CA. 90406		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Army Research Institute Attn: PERI-OK 5001 Eisenhower Ave., Alexandria VA 22333		12. REPORT DATE July 1981
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Navigation
Cognition
Reasoning
Learning

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Reverse Side

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

A series of studies undertaken to identify skills required for successful spatial performance. A Study of requirements for distance estimation, self-orientation, and object location tasks supported our assumption that the type of spatial knowledge acquired depends on the learner's information source. A second study showed that filmed traversal of an unfamiliar route provides as much knowledge about landmarks, landmark sequence, and distances as a live tour, but not sufficient information about angles of turns to allow accurate self-orientation. Studies of cognitive mapping skill showed that good mappers excel at acquiring knowledge from navigation or maps,at manipulating information in memory, and in visual memory, visualization, and spatial orientation ability. Good and poor mappers do not differ in map reading, map interpretation, or navigation skill. Examination of two different strategies for learning a new environment from navigation indicated potential benefits from training strategies compatible with the learner's abilities.

PREFACE

This report summarizes results from a two-year investigation at The Rand Corporation of human performance on spatial learning and reasoning tasks. Such tasks include learning object locations and spatial relations from a map and from navigation, reading and interpreting a map, using a memorized map to navigate in unfamiliar terrain, orienting oneself with respect to unseen locations, and estimating distances between locations on a map or in the terrain. This investigation, which was conducted between July 1979 and July 1981, was supported by the U.S. Army Research Institute for the Behavioral and Social Sciences under Contract No. MDA-903-79-C-0549.

The research described here was directed toward the eventual specification of training procedures and/or selection criteria for improving spatial task performance in the military. The major results reported, however, are immediately relevant to theories of spatial knowledge acquisition in general, and particularly to accounts of individual differences in spatial information processing skills. Thus, the report should interest researchers studying human abilities and human spatial cognition as well as practitioners in all the military services concerned with training and remediation of spatial skills. More detailed descriptions of the research summarized here may be found in the following companion publications:

- *Differences in Spatial Knowledge Acquired from Maps and Navigation*, by Perry W. Thorndyke and Barbara Hayes-Roth, N-1595-ONR, November 1980.
- *An Analysis of Cognitive Mapping Skill*, by Sarah E. Goldin and Perry W. Thorndyke, N-1664-ARMY, March 1981.
- *Ability Differences and Cognitive Mapping Skill*, by Perry W. Thorndyke and Sarah E. Goldin, N-1667-ARMY, March 1981.
- *Simulating Navigation for Spatial Knowledge Acquisition*, by Sarah E. Goldin and Perry W. Thorndyke, N-1675-ARMY, May 1981.

SUMMARY

Military operations often require the skilled performance of spatial tasks, such as learning an unfamiliar region through navigation or from a map, estimating distances between locations along a route or as the crow flies, estimating the bearing of an unseen location with respect to the current position, or reading and interpreting a map. Military training in spatial skills relies on ad hoc procedures derived from intuition rather than from theoretical principles. This research attempts to diagnose the skills required for successful spatial performance in order to provide a theoretical foundation for training.

Successful performance on spatial tasks depends on task requirements (e.g., requisite knowledge, alternative paths to a solution) and the cognitive resources available to the individual (e.g., memory capacity, solution strategies, ability to perform solution operations). Our empirical efforts examined both components. We began by identifying different types of spatial knowledge and their functions in common spatial tasks. We then conducted a series of studies investigating (1) alternative methods for presenting that knowledge, (2) differences in individuals' ability to acquire and use that knowledge, and (3) differences in their strategies for acquiring knowledge.

The first study investigated the knowledge requirements of several spatial tasks, including distance estimation, self-orientation, and object location. The results supported our assumption that the type of spatial knowledge acquired about an environment depends on the information source available to the learner. Studying a map generally produces what we term *survey knowledge*, a two-dimensional representation of the environment encoding global relations and straight-line distances between locations. Survey knowledge is shown to be optimal for estimating the shortest distance between two points and for determining the relative locations of objects. Navigating through an environment produces *procedural knowledge*, a linear, procedural representation encoding information about route distances and the angles between route segments. Procedural knowledge is optimal for estimating route distances and for orienting oneself toward unseen locations. With repeated navigation experiences, an individual also acquires survey knowledge. Thus, effective instruction about a novel environment should include navigation experience, to provide the broadest and most flexible environmental knowledge.

In many military situations, it is impossible or impractical to provide navigation experience in an environment prior to a mission. Therefore, our second study evaluated the feasibility of using film to simulate navigation as a spatial knowledge source. The results indicated that filmed traversal of an unfamiliar route provides as much knowledge about landmarks, landmark sequence, and distances as a live tour of the route. However, film does not provide sufficient information on the angles of route turns to allow accurate self-orientation performance. Providing a map along with the film significantly enhances knowledge of distances and spatial relations among locations beyond the level produced by a live tour.

The third set of studies investigated cognitive mapping skill and the sources of performance differences between good and poor cognitive mappers. Subjects were

categorized as good or poor mappers according to the accuracy of their survey and procedural knowledge about a familiar region and were then compared on a number of other spatial tasks. Good cognitive mappers excelled at learning an environment from navigation or from a map, and at manipulating spatial information in memory. They also scored higher than poor mappers on tests of visual memory ability, visualization ability, and spatial orientation ability, but not on tests of verbal ability. Good and poor mappers showed equivalent performance on map reading, map interpretation, and navigation tasks.

The fourth study examined two strategies for learning a new environment from navigation: a visual/perceptual strategy and a verbal/analytic strategy. The visual strategy emphasizes encoding visual information such as the appearance of landmarks, intersections, and other route features. This strategy leads to an orderly improvement in both survey and procedural knowledge over time. The analytic strategy emphasizes encoding street names and organizing spatial information into a schematic mental map based on compass directions. This strategy leads to an initially quite accurate survey representation that improves little with increased experience.

Individuals' basic ability profiles suggest the spontaneous strategies they adopt. Training effective strategies compatible with an individual's abilities may offer a promising approach to improving spatial learning and reasoning skills.

ACKNOWLEDGMENTS

Several individuals contributed to this report. Jackie Berman and Doris McClure conducted the experiments. Kay McKenzie prepared the manuscript. John Winkler and Richard Shavelson commented on an earlier draft of the report. We thank these colleagues and all of the subjects who generously gave their time to participate in our individual difference studies.

CONTENTS

I. INTRODUCTION

Military operations often require the skilled performance of spatial tasks. Such tasks include learning an unfamiliar region through navigation or from a map, estimating distances between locations along a route or as the the crow flies, estimating the bearing of an unseen location from a current position, and reading and interpreting a map. Locations are essential components of military operations. Nevertheless, many military personnel, including officers and well-practiced "experts," err on standard map reading and orientation tasks (Farrell & Potash, 1979; Simutis & Barsam, 1981). Army training in spatial skills relies on ad hoc procedures derived from intuition rather than systematic principles derived from theory. The effectiveness of this training may be substantially improved by diagnosing the skills required for spatial performance and deriving better methods to teach them.

This report summarizes an investigation of the psychological bases of spatial skills. We undertook this research to provide a theoretical foundation for improving selection and training of individuals to perform spatial tasks. We assume that successful performance on spatial tasks depends on both task demands (e.g., requisite knowledge, alternative possible solution paths) and the cognitive resources available to the individual (e.g., memory capacity, solution strategies, ability to perform solution operations). Thus, remediation efforts can focus either on providing the individual with additional cognitive resources (e.g., by teaching effective strategies) or on altering the task to fit existing human capabilities (e.g., by providing additional sources of information).

Our research examined both cognitive capabilities and task requirements. We began by adopting a theory that identified different types of spatial knowledge and their functions in common spatial tasks (Thorndyke, 1980, 1981; Thorndyke & Hayes-Roth, 1980). We then conducted a series of studies investigating (1) alternative methods for presenting that knowledge, (2) differences in individuals' ability to acquire and use that knowledge, and (3) differences in their strategies for acquiring knowledge.

Section II outlines our theoretical perspective and the evidence supporting it. A major conclusion derived from the theory is that extensive navigation through an environment can provide richer and more versatile spatial knowledge than studying a map of that environment. Section III focuses on the information requirements of learning through navigation by examining the utility of film as a learning medium. This section contrasts the knowledge derived from actual navigation with knowledge derived from filmed navigation and concludes that under some circumstances the two media provide equivalent knowledge. Section IV focuses on the human cognitive capabilities required by various spatial tasks. This section summarizes seven experiments comparing the skills and abilities of good and poor *cognitive mappers*, that is, individuals with accurate or inaccurate spatial knowledge of a familiar environment. Section V examines the strategies used in selecting and encoding information from the environment during navigation. The data reported in Section V indicate a relationship between ability, strategy choice, and the types of knowledge acquired. Finally, Section VI presents our conclusions regarding the improvement of spatial information processing performance in the military.

II. SPATIAL KNOWLEDGE REPRESENTATION

TYPES OF SPATIAL KNOWLEDGE

People acquire spatial knowledge from diverse types of experience: studying a map, navigating, viewing photographs, reading or hearing verbal descriptions or directions, and so on. Our research assumes that people derive three types of environmental knowledge from these experiences: landmark knowledge, procedural knowledge, and survey knowledge.* These types of knowledge differ in the aspects of the environment that they represent, the primary sources from which they are acquired, and the tasks in which they are most useful.

Landmark knowledge represents information about the visual details of specific locations in the environment. This knowledge presumably takes the form of perceptual icons, or images, of the sensory data they represent. People acquire such knowledge by directly viewing objects in an environment or by viewing indirect representations of the environment, such as photographs or film. Location recognition depends on accurate landmark knowledge. Such recognition presumably requires matching perceptual features of the current scene to representations of perceptual features stored in memory.

Procedural knowledge represents information about the sequence of actions required to follow a particular route. It includes explicit representation of points along the route where turns occur and the actions to be taken at each one. In addition, procedural knowledge implicitly represents distances along route segments, local orientation cues (i.e., directions of turns), and ordering of landmarks. Thus, this type of knowledge encodes the spatial relationship between two points in terms of the route connecting them. Procedural knowledge derives from the experience of navigating the represented route. Once acquired, procedural knowledge can be used to navigate or to mentally simulate navigation by imagining the sequence of landmarks and turns required in traveling between two locations. Mental simulation can be useful in computing spatial relations, such as estimating the distance between two points along the route or determining the direction for travel between two locations.

Survey knowledge represents the configural relations among locations and routes in an environment. This type of knowledge represents object locations and interobject distances with respect to a fixed, global coordinate system, as on a conventional map. Accordingly, survey knowledge can be acquired directly by learning a map. However, repeated navigation in an environment also leads to the development of survey knowledge (Siegel & White, 1975; Thorndyke & Hayes-Roth, 1980). Extended experience presumably allows an individual to coordinate different aspects of landmark and procedural knowledge, to make spatial inferences, and to gradually *abstract* the configural relations and straight-line distances among locations from perceptually grounded landmark and route knowledge. The map-like quality of survey knowledge makes it an efficient knowledge source for

*See Thorndyke (1980) and Thorndyke & Hayes-Roth (1980) for a more complete discussion.

estimating straight-line (euclidean) distances and for judging the absolute relation between two locations in a fixed frame of reference.

KNOWLEDGE INFLUENCES ON SPATIAL TASK PERFORMANCE

The knowledge taxonomy described above entails several predictions regarding how people acquire and use spatial knowledge. First, the predominant type of knowledge an individual acquires in a learning situation should depend on the source of spatial information. Procedural knowledge should be best acquired from navigation experience, while survey knowledge should be best acquired from studying a map. Second, individuals with *extensive* navigation experience should also begin to demonstrate relatively accurate survey knowledge. Third, the accuracy of spatial judgments should depend on the type of knowledge used to produce those judgments. Specifically, judging the bearing of unseen locations relative to one's current position in the environment and estimating route distances should be easier when based on procedural knowledge; estimating euclidean distances and locating points relative to a two-dimensional coordinate system should be easier when based on survey knowledge.

The third prediction relies on assumptions about the processing strategies used to compute each of these judgments. We assume that the most straightforward strategy for computing bearing (orientation) judgments and route distance estimates between two points depends on mentally simulating the route between those two points. Relative orientation can be "computed" by imagining the angle at each of the route turns and mentally updating an orientation vector at each turn. Route distance estimates can be computed by simply imagining the time needed to travel between the two points along the route, and then converting the time estimate to distance units. Procedural knowledge represents angles and distances directly, from the perspective of an individual traveling within the environment. Thus, the information needed for route distance and orientation judgments is immediately available. Furthermore, the orientation judgment task requires a *pointing* response from a "ground-level" perspective, the perspective of someone embedded within the environment. This is the perspective implicit in procedural knowledge, which represents memories of actual travel through the environment.

Survey knowledge, on the other hand, does not represent angle and route distance information directly; some kind of mental measurement process, such as "mental scanning" (Thorndyke, 1979), followed by some "mental arithmetic" to sum the lengths of legs, is required to compute route distances. More important, survey knowledge represents the environment from a "bird's-eye" perspective, from a point above the environment, looking down. Thus, making orientation judgments based on survey knowledge requires repeated mental shifts from a perspective "above" the environment to a perspective "within" the environment. This kind of perspective shift has been demonstrated to be quite difficult (e.g., Hintzman, O'Dell, & Arndt, 1981; Jankovic & Levine, 1979). Thus, we predict less accurate judgments of orientation and route distance based on survey information, because more difficult and complicated computations are required.

The same kind of argument leads to the prediction that euclidean distance estimates and location judgments should be easier when based on survey knowledge. Euclidean distances are explicitly encoded in a map-like survey representation; they must be derived through some kind of "mental triangulation" from procedural knowledge. Furthermore, the location task requires a response compatible with the bird's-eye perspective of a survey representation but incompatible with the ground-level perspective implicit in procedural knowledge. Thus, these two judgment tasks will require fewer and less-complex operations when based on survey knowledge.

In an experiment testing these three predictions (Thorndyke & Hayes-Roth, 1980), two groups of subjects judged various spatial relations between locations in the two buildings of The Rand Corporation, an environment containing a maze of halls, offices, and courtyards. One group having no prior exposure to the environment had memorized a map of the buildings' floor plan. The other group, consisting of Rand employees, had learned by navigating in the Rand corridors for periods of 1 to 2 months, 6 to 12 months, or 12 to 24 months. All groups were asked to judge the direction of specific locations in the building while standing at other locations (the orientation task), to estimate distances between points along specified routes (the route distance task), to indicate the locations of points relative to a fixed coordinate system (the map drawing task), and to estimate straight-line distances between landmarks (the euclidean distance task). As predicted, subjects who learned the map performed more accurately than navigation subjects on the map drawing and euclidean distance tasks, while navigation subjects performed more accurately on the orientation and route distance tasks. Thus, different kinds of knowledge appear to be optimal for different spatial tasks. Furthermore, increasing amounts of navigation experience produced improved performance on the tasks requiring survey knowledge, viz., map drawing and euclidean distance tasks. Individuals with 1 to 2 years' experience with the Rand environment performed as accurately on these tasks as subjects who learned the map.

These results suggest several conclusions. First, different kinds of experience result in different types of knowledge. Second, different kinds of knowledge are optimal for different spatial judgment tasks—this conclusion illustrates our earlier claim that performance must be considered as an interaction between task requirements and cognitive resources. Finally, navigation experience, when repeated over time, results in a richer and more complete knowledge base than does studying a map. Thus, navigation provides a superior knowledge source in situations that require retrieval and use of both procedural and survey knowledge.

III. SIMULATING NAVIGATION EXPERIENCE

The experiment described in the previous section indicated that repeated navigation through an environment leads to complete and accurate knowledge of that environment. However, in many military situations, acquiring such knowledge through actual navigation prior to the time the knowledge will be used may be impossible or impractical. For example, a commando team planning a mission to capture an embassy compound should be able to follow a designated escape route as well as improvise emergency routes, using knowledge about the orientation of known exits. However, such a team cannot actually navigate in the embassy compound to acquire the necessary spatial knowledge prior to executing the intended mission plan.

This example illustrates the need for providing procedural knowledge in ways that do not involve direct exposure to the environment. In cases where real navigation is impossible or impractical, *simulated navigation* may provide an alternative source of environmental knowledge. Full-sized mock-ups, slides or films, computer-generated graphics, and videodisc represent the range of media that can be used to simulate navigation experience. Each medium has advantages and disadvantages in terms of realism, flexibility, technical complexity, and cost. We chose the relatively simple and inexpensive medium of film to evaluate the basic feasibility of using simulated navigation as a source of spatial knowledge (Goldin & Thorndyke, 1981b).

This study addressed two questions: First, how does the knowledge acquired from simulated navigation compare with that acquired from actual navigation in content and accuracy? Second, can supplementary spatial information provided through a map or a verbal description improve learning from simulated navigation?

To answer these questions, we asked 96 subjects to learn a new environment, a 5.2-mile circuit in an unfamiliar area of Los Angeles. Half of the subjects received direct navigation experience in the form of a bus tour along the route. The other subjects viewed a 26-minute film taken from a car driving the same route. Within each of these experimental conditions, subjects received one of three kinds of supplementary information. The *map groups* studied a map of the experimental environment and route for 10 minutes before viewing the film or taking the tour. The *narrative groups* heard a verbal commentary that provided street names, distances, and directions while they watched the film or rode the bus. The *control groups* received no supplementary information. After exposure to the environment, all subjects were given tests of landmark knowledge (a location recognition task), procedural knowledge (location sequencing, orientation, and route distance tasks), and survey knowledge (map drawing and euclidean distance tasks).

Our first concern was the relative accuracy of film- and tour-group performance for each kind of knowledge assumed by theory. On the location recognition task, the film groups performed more accurately than the tour groups. This suggests that the film subjects focused their attention on perceptual detail to a greater extent than the tour subjects, who had a greater range of cues available. Thus, not surprisingly, film was shown to provide an effective source of landmark knowledge.

On tests of procedural knowledge, the results depended on the specific requirements of the task. The film groups performed as well as the tour groups on location sequencing (indicating which of two scenes shown on slides came first on the route) and route distance estimation (estimating distance along the route between landmark pairs). Results on the former task indicate that subjects in the simulated tour conditions had no difficulty acquiring the order information necessary to sequence locations. Results on the latter task suggest that the visual depth cues and motion sensations necessary to infer route distances were equally available in the simulated and actual navigation conditions. On the orientation task, however, the tour groups were significantly more accurate than the film groups. According to our theoretical framework, orientation judgments require accurate knowledge of the direction and magnitude of turns connecting route segments, as well as knowledge of the length of those segments. Since both groups of subjects estimated route distances equally accurately, the difference in orientation judgment accuracy must be attributable to differential knowledge of connecting turns. Subjects who actually rode along the route were free to look back after making a turn and coordinate several perspectives, unlike the film groups, who could only "look" straight ahead.

Finally, film and tour groups performed with equal accuracy on tests of survey knowledge; they did not differ on either the map drawing or the euclidean distance tasks. However, the absolute level of accuracy on these tasks was very low for both groups. These poor performance levels are consistent with our theory, which argues that survey knowledge develops from navigation experience only after repeated navigation opportunities.

The supplementary-information conditions produced mixed results. Only the film groups showed any effect of supplementary information, positive or negative. Presumably, the tour groups already had ample cues available and hence ignored cues provided by the map or narration. The film groups, on the other hand, received a relatively impoverished stimulus and hence may have actively sought information in the supplementary material.

Film subjects who viewed a map before their "tour" performed more accurately than control subjects on tests of survey knowledge (i.e., euclidean distance and map drawing tasks). As expected, by our theory, the map served as a direct source of survey information beyond the little global information that could be abstracted from a single navigation experience. On the other hand, map exposure *depressed* performance on the orientation judgment task, relative to that of the control group. It may be that subjects in the film-map group tried to use survey knowledge acquired from the map to compute orientation judgments, rather than relying on procedural knowledge acquired from the film. Our previous results showed that orientation judgments are more accurate when based on procedural knowledge than when computed from survey knowledge (Thorndyke & Hayes-Roth, 1980).

Finally, narration tended to depress rather than enhance performance in any condition where it had an effect. The complex verbal input apparently distracted film subjects from relevant spatial cues, without providing any information useful for the judgment tasks.

The results of this study suggest that simulated navigation can serve as an effective substitute for live navigation experience in certain situations. Film-based simulation provides an effective source of perceptual knowledge necessary for place recognition, sequence learning, and distance estimation. Filmed navigation, when supplemented by a map, is even more effective than live navigation as a source of survey knowledge.

While our conclusions are necessarily limited to film as a simulation medium, we believe that other media might be even more effective navigation surrogates (see Goldin & Thorndyke, 1981b). Simulation media, and particularly film, permit *a high degree of control over the information available to the learner*. This can be an enormous advantage, since the film-maker can select and focus on information relevant to the spatial learning task. Live navigation may not constrain the learners' attention sufficiently to ensure that they encode important cues. Our film deliberately avoided attentional biases as much as possible in order to provide a neutral test case. However, careful use of framing, zooming, and cuts in a simulation film might further improve the performance of subjects who view the film. Such techniques actually impose particular encoding strategies on learners who might otherwise select information less efficiently and effectively.

Film-based simulation also has promise as a medium for *training general encoding strategies*. Educational research has demonstrated that individuals can incorporate "perceptual operations" such as focusing on details and mental rotation from exposure to a film simulating these operations (Salomon, 1974, 1979). Similarly, films that simulate effective attentional strategies in a variety of environments, especially if supplemented with verbal instruction and/or practice, might allow viewers to incorporate these strategies into their repertoire for learning new environments.

IV. AN ANALYSIS OF COGNITIVE MAPPING SKILL

A large body of experimental research indicates that individuals vary widely in their spatial information processing skills (e.g., Chase & Chi, 1979; Kozlowski & Bryant, 1977; McGee, 1979; Thorndyke & Stasz, 1980). Some people have no difficulty in learning a route after a single traversal, in using a map to find their current position or to choose a route, or in discovering a new route using dead reckoning and their "sense of direction." Other people get lost in communities where they have lived for years, are confused by maps, or are unable to indicate the direction from their home to their place of employment. We sought to analyze the underlying sources of these individual differences, for two reasons. First, we wanted to understand "cognitive mapping skill" in terms of the cognitive resources necessary for effective task performance. Such an analysis of cognitive resources would suggest the particular skills, knowledge, and procedures that should be targeted for training. Second, such an analysis would indicate the mixture of stable and mutable factors that determine cognitive mapping skill. The identification of abilities underlying mapping skill could suggest criteria for selecting individuals with high aptitude for spatial knowledge and spatial skill acquisition.

This section summarizes seven studies investigating the nature of cognitive mapping skill. (These studies are described in detail in Goldin & Thorndyke, 1981a, and Thorndyke & Goldin, 1981.) Our goal was to develop a model of skilled spatial reasoning by contrasting the performance and abilities of good and poor cognitive mappers. We defined a good cognitive mapper as a person who had accurate procedural and survey knowledge of a familiar environment based on repeated navigation experiences.

Our subjects were selected from a large pool of individuals who were long-term residents of West Los Angeles. In an initial assessment, all individuals in this pool were tested on their procedural and survey knowledge of the West Los Angeles area, using variants of four tasks described in Section II: orientation, map drawing, route distance estimation, and euclidean distance estimation. We selected twelve subjects who showed consistently high accuracy on these tasks as our group of *good cognitive mappers*. Twelve subjects who showed consistently poor performance comprised our group of *poor cognitive mappers*.

THE EXPERIMENTS

The seven experiments summarized below attempted to isolate the factors responsible for the divergent performance of the two mapper groups. Our subjects were tested at intervals over a period of a year in order to assemble the body of data presented here.

Study 1: Providing Direct Survey Knowledge

One possible difference between good and poor mappers, we hypothesized, lay in their relative ability to abstract survey knowledge from navigation experience.

We attempted to equalize the survey knowledge of the two groups by providing this knowledge directly in the form of a map. If deficient survey knowledge abstraction accounted for the poor mappers' performance, their spatial judgments should improve after viewing a map of West Los Angeles.

About 6 weeks after the selection session battery, subjects were given a route planning task using a map of West Los Angeles. Following this task, subjects received the same set of four judgment tasks that had been used for subject selection. Poor mappers did not improve their performance at all, even though they had been exposed to survey information for at least 20 minutes immediately prior to the test battery. We concluded that either (1) deficient abstraction of survey knowledge was not the factor limiting the poor mappers or (2) poor mappers were also deficient in acquiring survey knowledge from maps. We examined these possibilities in Studies 5 and 2, respectively.

Study 2: Acquiring Spatial Knowledge from Maps

In this study we directly contrasted the map learning skills of good and poor cognitive mappers. Both groups attempted to learn two maps: a simplified map of Australia and a floor-plan map of the two Rand buildings. Subjects were given five study-test trials on the Australia map. On the Rand map, they were given as many trials as necessary to learn a specified set of map elements perfectly.

The results indicated that poor cognitive mappers learned less map information (e.g., lakes, cities, mountain ranges on the Australia map, corridors and public areas on the Rand map) than good mappers. Further, the poor mappers' memory for the detailed location of elements on the map was less accurate than that of good mappers. Thus, poor mappers seem to be deficient in recalling accurate survey knowledge from a map, as was suggested by Study 1.

Study 3: Acquiring Knowledge from Limited Navigation

Our assessment tasks demonstrated that good mappers have more accurate cognitive maps than poor mappers after extended navigation experience. Good mappers also acquired more accurate knowledge from maps, even on the first brief study trial. In Study 3, we examined the initial phases of learning from *navigation*. Each subject navigated by car a 4-mile route through an unfamiliar region, following directions marked on a map. After completing the tour, each subject received orientation, map drawing, route distance, and euclidean distance tasks based on the novel environment.

Results indicated that good mappers acquired more accurate knowledge than poor mappers from this single exposure to the environment. On each of the tasks, good mappers performed better than poor mappers. Furthermore, correlations between scores on these tasks and scores on corresponding tasks in the selection battery were uniformly high and positive. Thus, poor mappers appear to be deficient in the initial phases of knowledge encoding, as well as in the accuracy of their mature spatial knowledge.

Study 4: Reading and Interpreting Maps

An alternative explanation for differences between good and poor mappers in Studies 1 and 3 assumes that poor cognitive mappers are also deficient in map reading and map interpretation skills. If this is the case, poor mappers might have more trouble reading a map to follow a novel route and consequently would have less attentional resources available to encode spatial information. In Study 4, we compared good and poor mappers on a variety of map reading and map interpretation tasks. Subjects used conventional road maps to find locations, discover routes, and follow verbal directions to trace out a route. They also received training on topographic map interpretation and then used topographic maps to identify landform types and to visualize terrain.

Good and poor mappers did not differ significantly in their speed or accuracy on any of these tasks. Furthermore, scores for conventional map tasks did not correlate with topographic map task scores, suggesting that the two kinds of map reading require different skills. On the average, good and poor cognitive mappers can apparently demonstrate both sets of skills to an equal degree.

Study 5: Computing Spatial Judgments

Up to this point, we have assumed that good and poor cognitive mappers differ primarily in the accuracy of their spatial knowledge. However, they might also differ in the accuracy of the procedures they use to compute the spatial judgments required by our tasks. In order to evaluate the contribution of computational processes to the differences between the two groups, we examined a situation where the knowledge on which these processes operate was equated across groups.

In the map learning study (Study 3) all subjects had learned the Rand map to the same level of accuracy. After learning the map, subjects completed from memory a set of orientation judgments based on landmarks portrayed there (e.g., If you are standing at the computer center facing the door, which way is the snack bar?). Good cognitive mappers performed significantly more accurately than poor mappers, which suggests that good mappers excel both in their knowledge acquisition processes and in the computational procedures that operate on this knowledge.

Study 6: Navigation Based on a Memorized Map

In Study 6 we examined subjects' ability to use a memorized map as a guide to navigation. After all subjects had learned the Rand map perfectly (as described above), they were asked to select and navigate the most efficient route connecting a specified sequence of six landmarks.

This task revealed no reliable differences between good and poor mappers, either in the efficiency of their routes or in the time required to navigate those routes. Thus, when utilizing equally accurate knowledge, poor cognitive mappers can navigate as well as good mappers.

Study 7: Basic Abilities and Cognitive Mapping Skill

Psychometric research has identified a variety of *basic cognitive abilities* assumed to be components of skill in more complex cognitive tasks (e.g., Carroll, 1978; Horn, 1976). Three of these ability components seemed relevant to the encoding and computational differences distinguishing good and poor cognitive mappers: We hypothesized that good mappers might show superior *visual memory* (the ability to encode and retain purely visual information, as on a map), *visualization* (the ability to manipulate and transform a visual image in order to solve spatial problems), and/or *spatial orientation* (the ability to maintain a consistent frame of reference in a transformed or rotated visual array). The tasks on which the two groups differed in the earlier studies all required these types of mental operations. On the other hand, if cognitive mapping skill does depend specifically on spatial abilities, good and poor mappers should not differ in their *verbal associative memory* (the ability to encode and retain verbal information) or in their general *verbal ability* (a frequently used measure of overall intelligence).

In Study 7 we gave each subject standardized paper-and-pencil tests of visual memory, visualization, spatial orientation, verbal ability, and verbal memory. Results showed no differences between groups on the verbal measures. However, good cognitive mappers performed significantly better on the visual memory, visualization, and spatial orientation tasks. Thus, between-group differences found in complex spatial learning and judgment tasks examined earlier derive from differences in abilities to retain and manipulate spatial information.

IMPLICATIONS

These experiments have several implications for the selection and/or training of individuals to perform spatial tasks. First, "cognitive mapping skill" is not a unitary quantity affecting all spatial tasks. Good and poor cognitive mappers performed equally well on the map reading, map interpretation, and navigation tasks. Cognitive mapping skill has the greatest effect on tasks that require the encoding of spatial information and the manipulation of spatial information in memory. Thus, for these types of tasks, personnel should be selected on the basis of their cognitive mapping skill. However, map reading and navigation tasks, which represent a significant percentage of all military spatial tasks, do not seem to require these skill components and hence may not require selection.

Second, selection for cognitive mapping skill can be based on standard paper-and-pencil tests of basic spatial abilities (i.e., visual memory, spatial orientation, visualization). Lengthy assessment procedures like those used here to select subjects are not necessary.

Third, since basic abilities related to cognitive mapping skill are relatively stable attributes, the possibilities for improving cognitive mapping skill through training may be limited. If spatial abilities were the sole determinant of spatial task performance, attempts to train spatial skills could be difficult. However, as we noted earlier, performance on spatial tasks depends on both cognitive resources and task requirements. "Cognitive mapping skill" as indexed by actual performance will depend on an individual's strategies as well as his or her abilities, and particularly on the fit between those strategies and the task demands. The next section describes research investigating the spontaneous learning strategies adopted by different individuals and the effect of those strategies on the acquisition of different types of spatial knowledge.

V. INDIVIDUAL DIFFERENCES IN SPATIAL LEARNING STRATEGIES

THE TASK

To examine in detail the strategies individuals use to learn about a new environment and the relationship between those strategies and the knowledge acquired, we conducted an intensive pilot study of two individuals: a 21-year-old female (JT) and a 23-year-old male (DP). These subjects did not participate in any previously described study, and both were previously unfamiliar with Los Angeles. Each subject participated in five daily learning sessions. Each day, the subjects were driven over the same 20-mile route in West Los Angeles. They were instructed to learn the route, the appearance and location of seven specified landmarks along that route, and the general spatial layout of the area. As the experimenter drove along the route, subjects were encouraged to describe what they were noticing, any new features they were learning, and any inferences they were making. Their verbalizations were recorded on tape for later analysis of their strategies.

After completing the day's tour, subjects received tests of route recall, location recognition, location sequencing, orientation judgments, map drawing, and euclidean and route distance estimation. The location recognition test presented subjects with slides of landmarks, critical intersections (i.e., points along the route where a turn occurred), and non-critical intersections (i.e., intersections where no turn occurred), as well as scenes that had not occurred along the route. Subjects were required to indicate which scenes were drawn from the route. This test provided an index of the landmark, or perceptual, knowledge acquired by the subject.

On the route recall task, subjects verbally reproduced the route, describing it as if giving someone directions. This task measured the subjects' procedural knowledge, as did the location sequencing task, which required subjects to correctly order 42 slides of scenes from the route. Estimates of route distances between landmarks and judgments of the relative orientation of landmark pairs also provided indices of procedural knowledge.

On the map drawing task, subjects were asked to include all the information they could recall about Los Angeles, including the route and designated landmarks. This task indicated both the subjects' knowledge of location labels and the accuracy of their survey knowledge. The accuracy of subjects' estimates of straight-line distances between pairs of landmarks served as a second indicator of survey knowledge.

Subjects also received standardized tests of verbal associative memory, verbal ability, and several components of spatial ability (visual memory, visualization, spatial orientation). We administered these tests so that we could examine potential relationships between abilities and strategy choice.

SPONTANEOUS LEARNING STRATEGIES

Analysis of verbalizations during the learning sessions indicated large differences in the strategies adopted by the two subjects. The strategy used by JT could be characterized as *visual/perceptual*, while that used by DP could be labeled *verbal/analytic*.

Subject JT focused on perceptual features of the environment. She commented on the appearance of buildings, the characteristics of landscaping, and the general topography of the environment and the route (e.g., uphill, downhill, winding). She made explicit comparisons between scenes along the route and scenes from her past experience (e.g., contrasting the mountains to her home in Iowa). Aesthetic and affective judgments were common in her protocols. While she did not concentrate on learning street names, she did notice salient street signs and commercial signs. She made little attempt to organize her knowledge into a survey representation using compass directions; rather, she seemed to focus on the detailed perceptual and procedural knowledge available on the route itself.

Subject DP, in contrast, immediately adopted a grid-like framework and canonical compass directions to organize his knowledge. He concentrated on learning street names and attempted to encode his route knowledge into a series of verbal instructions (e.g., turn right at Ocean Avenue). He then attempted to use observations about relations among streets to establish a global, or survey, representation. For example, he noted that a particular street intersected the route at two different points and inferred that the two segments of the route were parallel. While he frequently generated such inferences and hunches about the relative locations and directions of streets or landmarks, he made fairly few observations about the appearance or visual characteristics of the terrain.

The strategies adopted by the two subjects bear some relation to their basic abilities. JT scored much higher on spatial ability components, especially visual memory, than on verbal ability, while DP scored high on both verbal and spatial abilities. The two subjects were roughly equivalent in verbal associative memory. JT appears to have adopted a learning strategy that capitalized on her strong visual memory and minimized demands on her verbal capabilities. DP adopted a more symbolically oriented strategy in accord with his high level of verbal ability.

INFLUENCES OF STRATEGY ON PERFORMANCE

The two subjects differed as markedly in their patterns of knowledge acquisition as in their strategies. Their relative performances on different tasks demonstrate the influence of their preferred strategies on the types of knowledge they acquired. Performance measures for their first and last days of learning are presented in Table 1.

Subject JT, who concentrated on perceptual features, showed more rapid and complete learning on the location recognition task, a index of landmark knowledge. Both subjects recognized landmark slides with fairly high accuracy that increased somewhat over days. However, DP performed much less accurately on critical and non-critical decision points than on landmarks, and he improved very little over days. JT, in contrast, showed a steady increase in perceptual knowledge for all

Table 1
PERFORMANCE SUMMARIES FOR SUBJECTS JT AND DP
IN EXTENDED NAVIGATION LEARNING STUDY

Performance Measure	Subject JT First Day	Subject JT Last Day	Subject JT Improvement	Subject DP First Day	Subject DP Last Day	Subject DP Improvement
Location recognition (% identified correctly)						
Landmarks	57	72	+15	60	90	+30
Critical intersections	14	57	+43	43	40	-3
Non-critical intersections	-5	34	+39	3	11	+8
Cumulative verbal knowledge (number of instances included on maps)						
Street names	9	25	+16	15	67	+52
Region names	0	8	+8	2	24	+22
Landmark names	2	33	+31	8	15	+7
Orientation judgments (mean angular error, deg)	104.7	24.6	+80.1[a]	34.3	26.4	+7.9
Route distance estimates (mean % error)	54.0	58.7	-4.7	36.4	32.4	+4.0
Map drawing/location (mean angular error, deg)	53.8	10.2	+43.6	9.4	8.8	+.6
Euclidean distance estimates (mean % error)	70.5	21.9	+48.6	62.2	52.2	+10.0

[a]Positive improvement values indicate reduction of error.

three stimulus categories. Clearly, she was continuously acquiring perceptual knowledge from all parts of the route, while DP was not.

Results from the map drawing task also indicate the influence of learning strategy. We used the maps to chart the cumulative acquisition of verbal labels for various types of spatial features in Los Angeles. As the center section of Table 1 indicates, the two subjects exhibited differential verbal knowledge even on the first day of testing. After the first day, DP's knowledge continued to increase more rapidly than JT's, particularly his knowledge of street names. This pattern reflects DP's overall strategy of noticing street names and trying to coordinate path connections.

Results from the judgment, distance estimation, and map drawing tasks suggest other knowledge differences deriving from strategy choices. Except for route distance estimates, JT showed substantial improvements on both procedural and survey knowledge tests over the course of the study. Her progress follows the course predicted by our theory, which postulates that repeated navigation experiences lead to both increasingly accurate procedural knowledge and the growth of survey knowledge. JT's continued attention to perceptual information in all five sessions led to increasingly precise knowledge of angles of turning and distances along route segments, knowledge necessary for accurate orientation and route distance judgments (see Section II). Her improving procedural knowledge also formed the basis for abstracting global relations among landmarks and learning the straight-line distances between landmarks.

DP's spatial judgment performance showed a very different pattern. His initial procedural and survey knowledge, as indicated by his judgment scores on the first day, was more accurate than JT's. However, DP's scores did not improve much with repeated experience, whereas JT was continually improving. DP's performance can be linked to his reliance on verbal/symbolic information and to his use of a two-dimensional framework to organize his knowledge. Apparently, DP shortcut the usual progression from landmark to procedural and thence to survey knowledge. He immediately converted his perceptions into a schematic "mental map," explicitly adopting a compass-grid framework. As the research reported in Section II indicates, judgments of euclidean distance and relative landmark location are more accurate when based on a map-like representation. Accordingly, DP could initially make survey judgments more accurately than JT. Over the course of the experiment, he elaborated this mental map to include more street names and path information. However, he did not particularly attend to perceptually based angle and distance information. As indicated by his protocols, his procedural knowledge was encoded verbally as a set of directions. Thus, he lacked the requisite information for effective mental simulation and for survey knowledge abstraction (see Section II).

Although DP and JT differed in their rates and patterns of knowledge acquisition, both assembled a reasonably accurate cognitive map after five days. This suggests that a variety of strategies can result in an adequate level of spatial learning. The selection of the appropriate strategy in a particular learning situation should thus be guided by the type of spatial information to be learned and by the basic abilities of the learner. The training of strategies for effective encoding, organization, and retrieval of spatial information is a promising approach to improving spatial learning and reasoning.

VI. CONCLUSIONS

This report summarizes a wide variety of studies addressing the roles of task requirements and human capabilities in spatial information processing tasks. These studies suggest a number of conclusions regarding the improvement of spatial reasoning skills in the military.

1. *Spatial knowledge sources should be selected on the basis of task requirements.* The study described in Section II indicates that different types of knowledge are optimal for different spatial judgments. In particular, knowledge of routes and relative orientations is best acquired from navigation experience rather than from a map. Extended navigation experience results in a more flexible and complete spatial representation than extended map study. In selecting a training medium for spatial knowledge, the eventual uses of that knowledge should be carefully considered.

2. *Simulated navigation should be used as a knowledge source when environmental access is restricted.* The results in Section III indicate that simulated navigation experience can provide substantial spatial information. Film-based simulation, supplemented by a map, may result in more effective spatial knowledge acquisition than actual navigation under some conditions. Simulated navigation may also be an effective means of training general spatial learning strategies.

3. *Selection of individuals should be based on task requirements.* Some, but not all, spatial tasks require high levels of spatial ability. Section IV indicates that map using and spatial knowledge acquisition tasks require independent sets of skills, and that only for the latter is performance related to cognitive mapping skill.

4. *Selection of individuals should be based on basic abilities.* Spatial reasoning skill is highly related to psychometrically defined components of spatial ability. An individual's scores on tests of visual memory, spatial orientation, and visualization can be used to predict his success on complex tasks such as learning a new environment from navigation or from a map. Spatial ability scores might also be used to select instructors for training other personnel in spatial skills, at least to the extent that spatial abilities are linked to effective strategies.

5. *Spatial information processing strategies that are appropriate to the individual and the task should be trained.* This conclusion is based on our preliminary findings reported in Section V. Research in map learning has shown that effective strategies can be trained and that effective use of strategies is somewhat dependent on basic ability. If the strategies used by good cognitive mappers can be identified and incorporated into current training programs, instruction may significantly improve the average level of spatial learning and reasoning performance in the military.

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